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EXPERIMENTS ON THERMAL CONVECTION IN ROTATING SPHERICAL SHELLS WITH RADIAL GRAVITY: THE GEOPHYSICAL FLUID FLOW CELL

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ABSTRACT

Experiments designed to study the fluid dynamics of buoyancy driven circulations in rotating spherical shells were conducted on the United States Microgravity Laboratory II spacelab mission. These experiments address several aspects of prototypical global convection relevant to large scale motions on the Sun, Earth, and on the giant planets. The key feature is the consistent modeling of radially directed gravity in spherical geometry by using dielectric polarization forces. Imagery of the planforms of thermally driven flows for rapidly-rotating regimes shows an initial separation and eventual merger of equatorial and polar convection as the heating (i.e. the Rayleigh number) is increased. At low rotation rates, multiple-states of motion for the same external parameters were observed.

INTRODUCTION

The existence of extremely strong and axisymmetrically banded zonal winds on the giant planets represents one of the most outstanding problems in planetary science (Ingersoll, ref. 1). Several theories have been proposed (Busse, ref. 2, Dowling, ref. 3, Marcus and Lee, ref. 4), but recent data from the Galileo immersion probe, which showed strong winds increasing with depth in the Jovian atmosphere over many scale heights, seems to lend support to those theories (e.g. ref. 2) that couple the observed cloud top zonal winds with deep convection. It is postulated that such deep convection, under the influence of sphericity and strong basic rotation of the planetary atmosphere, can organize and generate substantial zonal winds through wave interactions. Indeed, high resolution three-dimensional numerical models (e.g. Sun et. al., ref. 5) have shown that banded zonal winds (albeit very weak ones) can be formed by such processes. Similar mechanisms have been proposed to explain the differential rotation of the Sun (e.g. Gilman, ref. 6). One important aspect of these models is the existence of columnar "banana cell" convection, aligned with the rotation axis. Nonlinear interactions of the convective columns generate zonal flows. One may ask why we don't see the tips of the banana cells in the cloud patterns of Jupiter, for example. Idealized, but extremely high Rayleigh number calculations of Brummel and Hart (ref. 7), show that it is possible for **weak** convective columns to generate **extremely fast** zonal jets. In this case the motion field is dominated by the jets and it becomes difficult to observe the underlying convection cells. Additionally, these computations showed that the whole zonal-flow / convective-column system can pulsate, leading to alternating bursts of convective turbulence, then enhanced zonal jets. Burps of convection on Saturn (e.g. Sanchez-Lavega, ref. 8) are similar in appearance. Because the Brummel-Hart model is two-dimensional (by the Taylor-Proudman constraint), it would be interesting, but very difficult, to extend 3-D models into the appropriate parameter range for strong jets and pulsations. Alternatively, laboratory experiments may be used to test some of the simulation results.

Laboratory models can play an important role in contributing to our understanding of geophysical flows. However, to be relevant for astrophysical and planetary application lab experiments must replicate the unifying features of planets and stars: they are spherical with centrally directed radial gravity, they rotate at various magnitudes, and motions are driven thermally in response to different types of heating. Of these criteria the first is the most difficult to satisfy, because in the terrestrial laboratory gravity is unidirectional, so in any

rotating experiment the rotation vector and the gravity vector maintain a fixed relative orientation. In order to overcome this obstacle we have developed a method for studying thermally driven convection within a rotating spherical shell of fluid, using electro-hydrodynamic polarization forces to generate the required **radial** buoyancy forces. However, the radial forces are relatively weak, about 0.1 g, and so are overwhelmed by terrestrial gravity. Thus the microgravity spacelab environment is uniquely suited for experiments of this type. The instrument, called the Geophysical Fluid Flow Cell (GFFC), initially flew on Spacelab-3 in 1985 and the results were reported in Hart, Glatzmaier and Toomre (ref. 9). A reflight on USML-2 in 1995 permitted observations over a wider range of parameters while using a different imaging procedure designed to facilitate the acquisition of data on the time-dependence of convective states. The fundamental principle of the experiment is briefly explained below, followed by a short summary of the preliminary results from USML-2.

DESCRIPTION OF THE EXPERIMENT

Figure 1 shows a cross-section of the GFFC. The inner spherical shell is a nickel-plated mirror. The outer shell is a transparent sapphire hemispherical dome with an electrically conducting coating applied to the inner surface. The inner and outer radii are $R_i = 3.3\text{cm}$ and $R_o = 2.4\text{ cm}$, respectively. A 300 Hz. a.c. voltage V is applied across the dielectric 0.65 centistoke silicone fluid contained in the gap. The resulting radial electric field leads to a centrally directed polarization force which is nearly linear in the liquid density, with magnitude proportional to the square of the applied voltage. As shown in ref. 9, the equations of motion for the silicone oil in zero-g are isomorphic to those for a Boussinesq thermally convecting liquid in a spherically symmetric geopotential that goes like inverse radius to the fourth power, provided dissipative electrical heating (which is a small effect) is neglected. Studies of the linear instability problem in spherical shells with varying gravity distributions show that for the aspect ratio of the GFFC experiments, $R_i/(R_o-R_i) = 2.65$, the linear eigenfunctions with r^2 vs. r^3 gravity distributions are nearly identical.

Motions are driven by imposing various thermal distributions on the inner and outer shells. If the inner sphere is at a uniform temperature hotter than the constant temperature outer wall, then unstable convective motions in the radial electrostatic gravity field are excited by this spherically symmetric heating distribution. Such forcing boundary conditions are relevant for modeling the Sun and the Earth's mantle, where the driving is thought to be symmetric. However, latitudinal (as well as radial) gradients of applied heating can be imposed, modeling, perhaps, situations where rotating convective motions are driven by external latitudinally-dependent solar fluxes, as well as by a symmetric internal heat source (e.g. Jupiter). The degree of heating is measured by the standard Rayleigh number $Ra = g\gamma\Delta Td^3/\kappa\nu$, based on the applied temperature difference and the magnitude of the imposed electrostatic gravity g (proportional to V^2 , with a maximum of about 0.1 g). Here γ is the variation of permittivity with temperature, κ is the thermal diffusivity, and ν is the kinematic viscosity. In the GFFC Ra ranges from 0 to about 2×10^6 . The relative degree of rotation is measured by the Taylor number $Ta = (2\Omega d^2/\nu)^2$ based on the gap width, rotation rate, and fluid viscosity. Low rotation regimes have $Ta < 1000$ or so, while the maximum attainable value in the GFFC is about 10^6 .

Flows are visualized by a back-focus Schlieren system giving information on the radially averaged temperature structures in the convecting liquid. Data were recorded on 16mm film for post-mission processing and analysis, and the images were also relayed to ground during the mission to enable near real-time changes in the experiment protocols (e.g. changes in Ra , Ta , heating distribution, etc.). The video and 16mm data comprise the main data sources, with the former containing a limited and the latter having a more substantial imbedded record of the experiment parameters (e.g. high voltage, time, temperatures measured at various points by thermistors, etc.). For more extensive discussion of the instrument see ref. 9.

RESULTS

Instrument performance. The Geophysical Fluid Flow Cell Experiment carried out 29 separate 6 hour runs using different parameters (cell rotation rate, heating distributions, etc.). Eighteen of the runs were nominal in terms of instrument performance, except for indications that suggested higher than expected temperatures along the outer sphere's equator. Because of this overtemperature problem, science activities were focused on situations with spherically symmetric heating (the so-called "solar model" cases). The last eleven runs were affected by the failure of the 16mm film transport, leaving the video as the primary data source. This was compensated for by running experiments towards the end of the mission with commanded boundary temperatures similar to those run earlier in the mission on which film data is available.

Scientific Results: The following are the preliminary results based on video downlink recorded during USML-2 (analysis of the 16mm film data has just commenced). The experiments fell into several classes depending on the rotation rate (rapid or slow: e.g. solar-like or mantle-like). In each case new states were observed and are summarized below.

1) Studies of rotating convection with spherically symmetric heating revealed possible multiple jets in latitude, with prograde (same sense as the basic rotation) motion of thermal waves at low and high latitudes and retrograde pattern rotation at mid-latitude (see figure 2). Such differential pattern propagation has not been previously seen in computational models, and these results may provide an alternative view on the mechanisms for "banded"-looking structures in planetary atmospheres like Jupiter. However, contrary to suggestions from our Taylor-column idealized models, no vacillatory (periodic global pulsation) states were observed.

2) An extensive study of slowly rotating convection was carried out, and two distinct convection patterns were observed in experiments with the same external parameters but with different initial conditions. This means that the long-time evolution of modestly convecting flows in slowly rotating spherical shells (like earth's mantle) is not unique, but depends on initial conditions. Equivalently the "climate" can be persistent, or locked, for long times as external conditions change slowly. In addition, information was obtained on how these persistent states evolve as parameters are increased across stability boundaries. Figures 3a and 3b illustrate the instability of "horseshoe convection", wherein the off-center ring of convection breaks down by north-south oriented stripe formation as the voltage is increased from 1.44kV to 1.56 kV.

3) A large data set (several different rotation rates, many different heating rates) was obtained on the transition between anisotropic north-south oriented "banana convection" and more isotropic non-aligned convection. These results, when quantified by digital analysis of the data films and tapes, will permit testing of simple scaling arguments for this transition. Once verified, these scalings can be used to classify the expected global convection regimes of planets and stars.

4) Experiments with latitudinal heating gradients showed evidence for baroclinic waves. This instability is interesting because it has combined attributes of both ordinary thermal convection and rotating slantwise convection. The latter instability is central to the circulation of the earth's atmosphere, but its occurrence as a combined instability supports recent computational modeling of such instabilities in rotating spherical shells.

5) Other experiments with latitudinal heating showed how spiral wave convection breaks down to turbulence by secondary branching.

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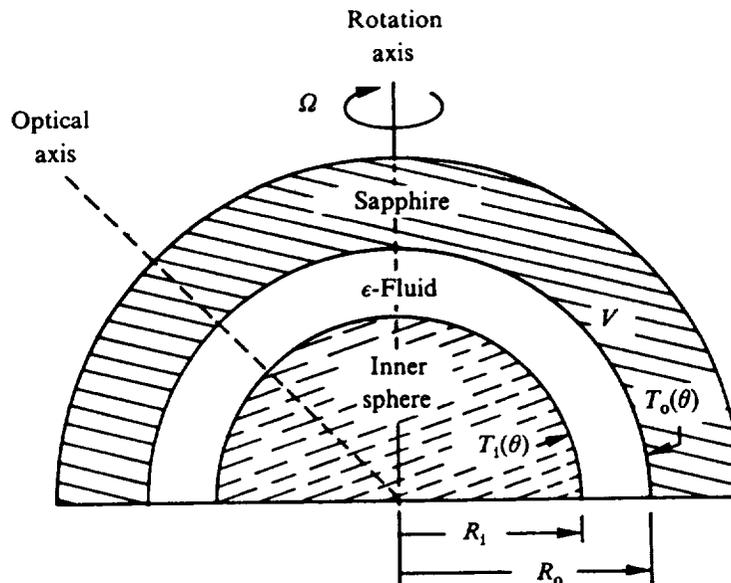


Figure 1. Cross-section of the test cell used to study global convection in a rotating hemispherical shell of fluid in the presence of an electrostatic radial gravity field. That gravity is achieved by imposing an alternating potential V (0 to 10 kilovolts) across the fluid shell.



Figure 2. Schlieren map of a turbulent “solar-model” case with rapid rotation and spherically symmetric heating. The equator is at the top of the picture and the pole is at the bottom. The features propagate prograde at the bottom and top of the frame, while moving retrograde at mid-latitude.

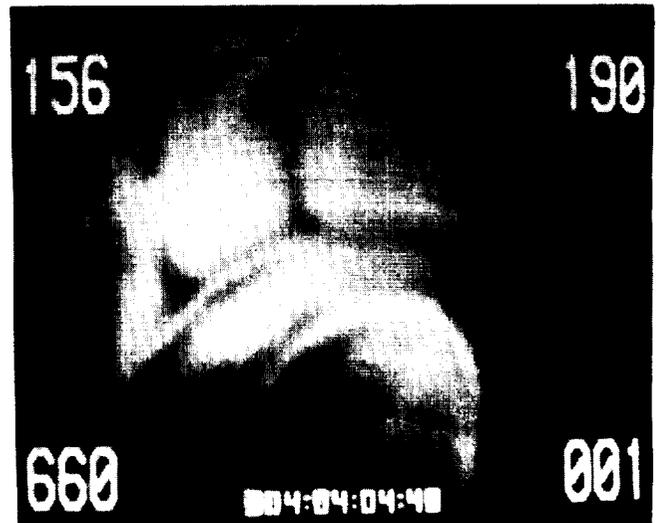
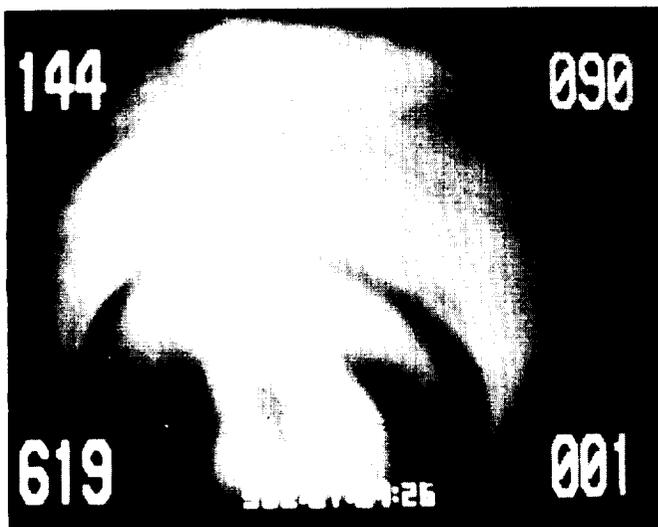


Figure 3. A stable low rotation convection state consisting of an off-axis polar convecting ring (left). As the voltage (i.e. gravity) is increased this nearly axisymmetric state breaks down as columnar modes appear, extending from mid-latitude down into the tropics (right). The equator is at the top and the pole at the bottom.

